Stochastic fluid structure interaction of a flat plate facing a uniform flow

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Abstract

An experiment of a flat rectangular plate facing a uniform flow at Re=264000 shows the importance on the base pressure loading of the asymmetric static modes of the turbulent wake. The plate is free to rotate around its small symmetry axis. For plates with aspect ratio $\kappa<6$, the angular position exhibits strong random discontinuities between steady states of large non zero angles. The steady states have long time durations, more than one order of magnitude larger than the convective timescale. The discontinuities, comparable to violent and unexpected events are due to strong fluid forces associated with the drastic global change of the three dimensional wake, mainly the switching between static asymmetric modes.

Keywords: Stochastic; Symmetry breaking; Fluid structure interaction; Non Gaussian statistics.

1 Introduction

It is known that for three dimensional bodies, the first bifurcation in the flow solution as the Reynolds number is increased leads to steady symmetry breaking modes. This has been demonstrated for axisymmetric bodies [1][2][3] and for bodies having rectangular blunt base[4][5]. At low Reynolds number, these steady modes play an important role in problems of fluid structure interaction, such as for instance the dynamics of falling bodies [6]. Recently, steady symmetry breaking modes have been evidenced at large Reynolds numbers, leading to random multistable dynamics. For bodies having a reflectional symmetry such as the Ahmed body, Grandemange *et al.* [7] have shown that the wake is bistable with a long time dynamics of random switching between two mirror symmetry breaking modes.

As shown in [5], simple rectangular plates are subjected to these steady symmetry breaking modes in the laminar regime and one may wonder how they can interfere in the case of fluid structure interaction at large Reynolds numbers. The purpose of this work is to study the consequence of such static symmetry breaking modes dynamics on a very simple fluid structure interaction experiment involving a three dimensional turbulent wake. It will be evidenced that the switching between these symmetry breaking modes leads to rare and violent events on the plate motion.

2 Experiment

The mechanical system is a simple plate that rotates freely around its small reflectional symmetry axis as depicted in Fig.1. The plate is made of plexiglass, its thickness L is 6mm, the height H is 48mm. Aspect ratios κ=H/W ranging from 1 to 8 are investigated with plates of different widths W. The plates are pierced with a hole of 4.2mm in diameter at the position H/2. A rod (the axis of rotation), with a diameter of 4mm made of brass and lubricated with silicon oil is passed through the hole. The plate is then free to rotate around a fixed axis. Two teflon annuli avoid the plate to slide along the rod. We denote θ the angle between the plate and the vertical unit vector, taken as positive in the clockwise direction. The plate angular velocity, expressed in rad.s^{-1} is Ω .

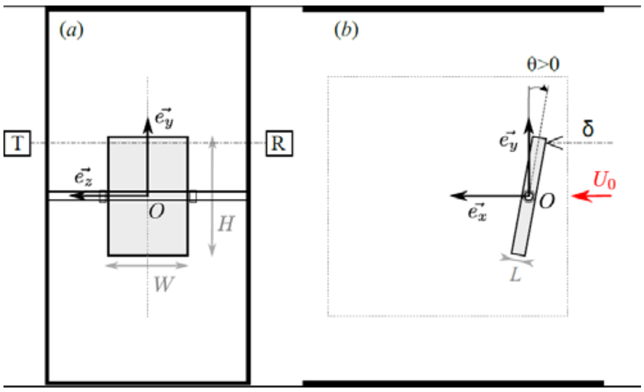

Fig.1 Water tunnel facility and flat plate set up.
Cross section view (a) and side view (b).

The dynamical system is placed in a hydrodynamics tunnel of cross section 150×80mm. The test section is 800mm long and completely transparent. The fluid is water (ρ = 1000kg/m^3). The main flow velocity is set to U_0=5.5m.s^{-1}, such that the Reynolds number defined as Re= U_0H/ν=264000. There is no cavitation during the experiments unless during the visualisations for which the pressure has been reduced to produce enough bubbles to seed the wake. A Pegasus dual pulse 8 mJ Nd:YLF laser and a camera Photron APX RS with a resolution of 1024×1024

pixels are employed. The shutter of the camera is set to 60Hz and the repetition rate of the laser to 2kHz. As a result, bubble trajectories reveal the flow structure over a non dimensional duration of $dt^*=1/60 \cdot U_0/H=1.91$.
For accurate measurements of the angle, we use a high speed and high precision optical Keyence micrometer (LS-7070M) constituted by a transmission unit (T in Fig. 1a) which emits light and a receiving unit (R in Fig.1a) which detects the position of the shadow of the targeting object. The micrometer has an accuracy of ±3μm and a sampling frequency of 2000Hz. In our case, it detects the horizontal position of the superior edge of the plate facing the flow as indicated by the δ position in Fig.1(b). The estimated accuracy for the angle measurements is $\Delta\theta=\pm 0.01°$.

3 Results and Discussion

We will consider two aspect ratios only, $\kappa=6.85$ and $\kappa=3.43$. The corresponding angle time series in Fig.2 and spectra in Fig. 3 are very different. For the large aspect ratio, the plate response is very similar to a simple linear system excited with a random white noise $\xi(t)$:

$$\ddot{\theta} - \gamma\dot{\theta} + \omega_0^2\theta = \xi(t) . \qquad (1)$$

The response power spectrum of the dynamical system (1) reads :

$$\left\langle \left|\tilde{\theta}(\omega)\right|^2 \right\rangle = \frac{\left\langle \left|\tilde{\xi}\right|^2 \right\rangle}{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2} \quad , \qquad (2)$$

which superimposes satisfactorily to the experimental measurements in Fig.3.

In the case of the lower aspect ratio, the angle undergoes much larger deviations, keeping same signs for very long time durations (more than hundreds natural timescale). The only characteristic frequency in the spectrum in Fig.3 marks the beginning of a power law decrease at about $f^*=2.10^{-2}$ with an exponent close to -3 over more than one decade.

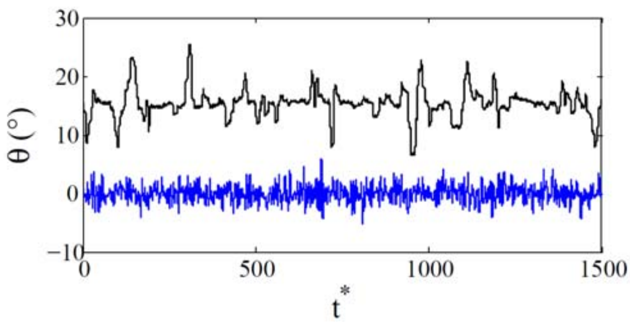

Fig.2 Angle time series for plates of aspect ratio κ = 6.85 (blue) and κ = 3.43 (black, artificially shifted by 15° for clarity).

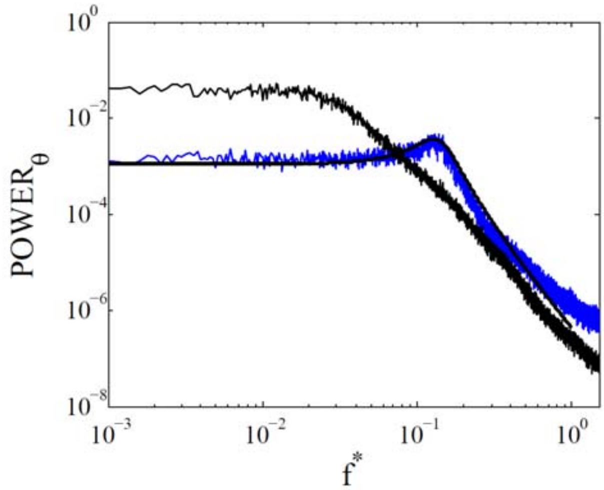

Fig.3 Power spectrum of the angle for plates of aspect ratio κ = 6.85 (blue) and κ = 3.43 (black). The black line is the linear model (2) with $\gamma^*=0.5$ and $f_0^*=0.13$.

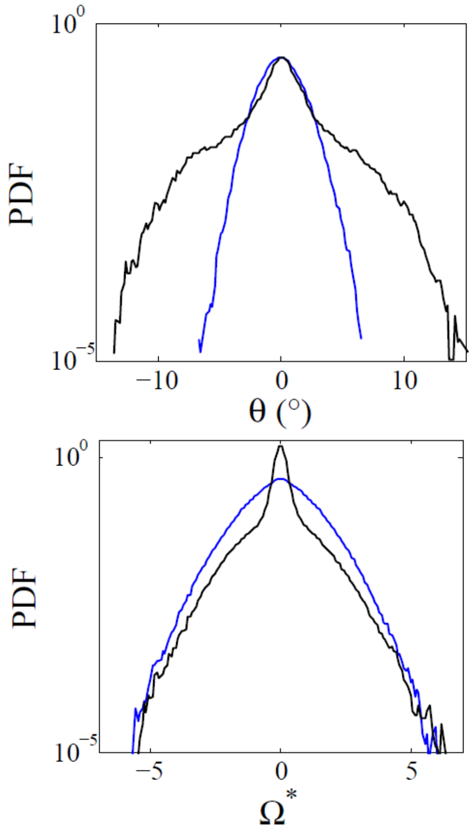

Fig.4 Probability density function of the angle (top), and angular velocity (bottom) for plates of aspect ratio κ = 6.85 (blue) and κ = 3.43 (black)

The exponent is related to the random occurrence of events of large deviations. These events are better quantified with the probability density function of the angle displayed in Fig. 4 (top). While the statistics is Gaussian for κ=6.85 as expected for a linear response of the random white noise forcing, it spreads extended tails for κ=3.43 showing extreme events of very large angle deviations. However, the extreme events of angular velocities are similar for both dynamics in Fig.4 (bottom). The striking difference relies in the excess of event of zero angular velocity for the κ = 3.43 plate. It is due to the presence of plateaus in Fig. 2, equivalent to static states, having random lifetimes.

Violent events are generally associated with large fluctuations compared to the typical one, it is then interesting to plot both statistics against their variable reduced by the standard deviation. As can be seen in Fig.5, for the angle and the angular velocity, it is much more probable to observe a violent event, both in angle deviations and large velocities with the lowest aspect ratio plate.

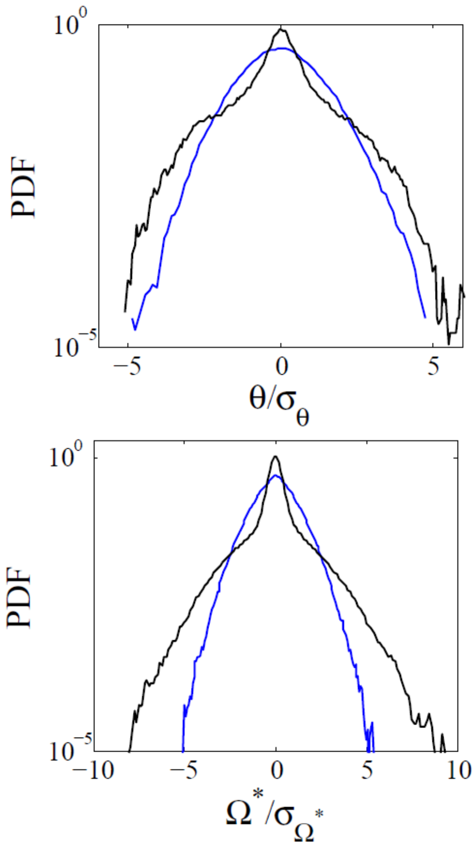

Fig.5 Probability density function of the reduced angle (top), and reduced angular velocity (bottom) for plates of aspect ratio κ = 6.85 (blue) and κ = 3.43 (black)

Flow visualizations and PIV measurements (not shown here) reveal the complex wake dynamics responsible for the stochastic behavior of the case κ = 3.43. The wake is often clearly asymmetric, as shown in Fig.6, with a large and intense circular recirculation close to the base either located on the bottom hand side (Fig.6, left) or on the top hand side (Fig.6, right). It has to be remember from above, that these static states (I.e. the angle keeps constant value) can have extremely long lifetimes compared to the natural timescale of the flow H/U_0. The torque balance can be guessed from the pictures. While the intense recirculation in the wake associated with a low pressure (higher concentration of bubbles) creates a torque, the pressure distribution upstream the inclined plate produces a torque with an opposite sign.

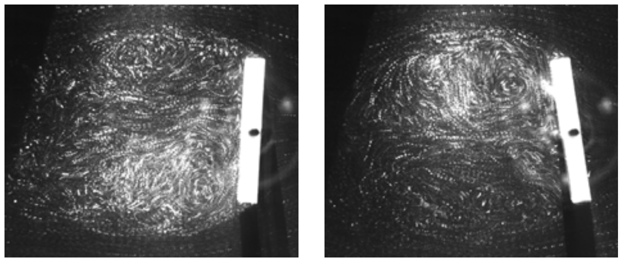

Fig.6 Flow visualization using bubbles technique showing some extreme events of angle for the plate free to rotate and having an aspect ratio κ = 3.43.

The key ingredient for the stochastic fluid structure mechanism is actually based on the fact that when the plate is fixed, the stable wake is always reversed compared to that of the same inclination of the free plate. The fixed inclination then produce a global positive hydrodynamics stiffness with an equilibrium at θ=0. Thus,when the plate is free to rotate, the wake asymmetry produces a torque that inclines the plate in an unstable situation producing a wake reversal.

3 Conclusion

The stochastic dynamics is related to the existence of static symmetry breaking modes in the turbulent wakes of three-dimensional bluff bodies. In the case of the free to rotate flat plate, these static modes are able to create a violent an unintuitive dynamics. A model similar to (1) but with a stochastic forcing based on the probability of presence of the symmetry breaking modes with the angle now needs to be investigated.

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